



MOKELUMNE WATERSHED AVOIDED COST ANALYSIS:

# Why Sierra Fuel Treatments Make Economic Sense



# Appendix A - Fire Modeling

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## A.1 Assessing Wildfire Hazard

Hazard is a physical situation with potential for causing harm or damage. Wildfire hazard can be quantified by combining the likelihood of experiencing a wildfire with the intensity, or severity, of that wildfire if it were to occur. Two geospatial fire modeling systems—FSim and FlamMap5—were used to quantify wildfire hazard in the Mokelumne watershed and the surrounding landscape, in both a baseline (circa 2008) and a hypothetical treatment scenario.

### A.1.1 Fire SIMulation system (FSim)

FSim, a large-fire simulator, was first developed for the Fire Program Analysis (FPA) project (<http://fpa.nifc.gov/>). FSim is a comprehensive, stochastic fire ignition, growth, and suppression simulation system that pairs a fire growth model (Finney 1998, Finney 2002) and a model of ignition probability with simulated weather streams in order to simulate fire ignition and growth for tens of thousands of fire seasons. The results of these simulations are used to estimate annual burn probability (BP) for each grid cell across a landscape. In FSim, annual BP is estimated by dividing the number of simulated fires that burned each pixel by the total number of simulated fire seasons. We used FSim (Finney and others 2011) to determine geospatial burn probability across the Mokelumne landscape.

In addition to the gridded BP results, FSim also produces an ESRI shapefile containing the final perimeter of each simulated fire. The perimeter results are useful for assessing risk to watersheds. With the perimeters it is possible to calculate the probability of fire reaching any part of a watershed, and the distribution of watershed area burned. Moreover, the fire perimeter results can be combined with gridded fire effects modeling, such as sediment production, and polygon-based fire effects modeling, such as debris flow likelihood and volume, to estimate conditional and expected fire and post-fire effects. FSim's gridded and fire perimeter results have been used for spatial risk analyses in a number of contexts (Scott et al. 2012a, 2012b; Thompson et al. 2011, 2013a, 2013b).

Simulation of daily values of Energy Release Component (ERC) of the National Fire Danger Rating System is the foundation of FSim's operation. ERC is calculated from historical weather data (Cohen and Deeming 1985). The simulated ERC is used in two ways: first, to determine the probability of a fire start for each day, and second, to determine which of three fuel moisture scenarios to use for the day. The three scenarios correspond to ERC classes with breaks at the 80<sup>th</sup>, 90<sup>th</sup>, and 97<sup>th</sup> percentile ERC values. ERC is simulated for each day of each simulated fire season based on the historic seasonal trend in mean and standard deviation of ERC using temporal autocorrelation (Finney *et al.* 2010). Fire growth occurs only on days for which the simulated ERC exceeds the 80<sup>th</sup> percentile. Simulated fire growth for each day of each fire is also a function of wind speed and direction. Wind characteristics for each day are determined by a random draw from the historic monthly joint frequency distribution of wind speed and direction. This draw is independent of ERC, and each day's draw is independent of the others.

A wildfire in FSim grows until it is either contained or self-extinguishes. FSim includes a suppression module based on a containment probability model (Finney et al. 2009) that relates the likelihood of fire containment on a given day to current and previous fire growth. Containment success is simulated stochastically based on comparison of a random draw with the modeled containment success probability. Self-extinguishment occurs when ERC remains below the 80<sup>th</sup> percentile value for several days in a row.

FSim produces an estimate of the circa 2008 burn probability, not estimates of burn probability for future fire seasons. In FSim, the fire modeling landscape (LCP – for landscape) remains unchanged between fire simulations and fire seasons; there is no attempt to simulate how simulated fires may affect future fire growth. FSim is parameterized and calibrated based on past weather and fire occurrence, typically going back about 20 years. However, the last decade has been dryer than the previous decade, therefore going back 20 years for fire history may undervalue the intensity and probability compared to what is currently being experienced. Research efforts are now underway to simulate fire likelihood under a changing climate with FSim, but those methods are not yet available for use on this analysis. FSim is designed primarily to illustrate how fire likelihood is distributed spatially across a landscape in relation to ignition density and fire growth potential. The absolute level of likelihood is assumed to be roughly equal to that indicated by past fire occurrence. If that is not the case, FSim's results could under- or over-estimate actual BP, and based on the recent shift in fire behavior from historical patterns, it is possible that in this case it is under-estimating the actual BP.

### **A.1.2 FlamMap5**

Although FSim has the capability of modeling fire intensity, early in our process we decided that FSim's fire intensity results under-represent low-probability, high-intensity events. Therefore, the FSim simulations were used solely to estimate burn probability; potential fire intensity and the propensity for crown fire under severe conditions was estimated with FlamMap5 (Finney 2006).

FlamMap5 is a spatial fire behavior model that computes potential fire behavior characteristics such as rate of spread, flame length, and fireline intensity over the entire LCP with constant weather and fuel moisture conditions. FlamMap5 creates raster data of these fire behavior characteristics. This raster data can be viewed directly in FlamMap5 or exported for use in GIS. There is no temporal component in FlamMap5, it uses the spatial data in the LCP to calculate fire behavior characteristics, including the type of fire (surface fire, passive crown fire, or active crown fire), rate of spread, fireline intensity, and flame length. A single set of environmental conditions is used to produce a "snapshot" of potential fire behavior. In contrast to FSim, FlamMap5 calculations are made for the heading direction only, thus representing a conservative estimate of the fire behavior that could occur at the grid cell.

## **A.2 Model Inputs**

Three broad classes of inputs are required for running FSim and FlamMap5: 1) a fire modeling landscape (LCP), which describes fuel, forest vegetation, and topography across a landscape, 2) historical weather, and 3) historical fire occurrence.

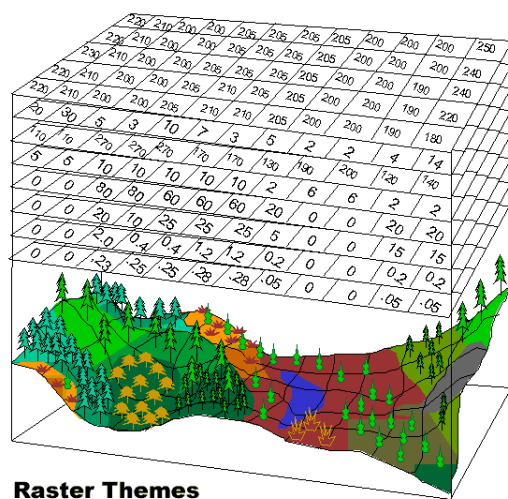
### A.2.1 Fire modeling landscape

Spatial fire models need a virtual landscape on which to simulate burning. This virtual landscape—called a fire modeling landscape—is a set of gridded (raster) data layers, as shown below. On the Mokelumne LCPs, each grid cell (pixel) represents a square that is 30 meters on a side, representing approximately 0.22 acres. The Mokelumne LCPs consist of 10,248,068 grid cells representing 2,279,118 acres. This LCP size includes a buffer around the Mokelumne watershed so that FSim can simulate fires that ignite outside the watershed but burn into it.

The LCPs consist of data layers representing elevation, slope, aspect, surface fuel model, canopy cover, canopy height, crown base height, and crown bulk density (Figure A.1). To estimate first-order fire effects and tree mortality outputs, a fuel-loading model and tree list are needed.

LCPs representing two landscape conditions—current and treated—were created for this project. The current-condition LCP represents fuel and forest vegetation as it existed circa 2008; the treated-condition LCP represents fuel and forest vegetation as it might exist on the same circa 2008 LCP after implementation of fuel treatments across a designated portion of the watershed.

**Figure A.1**



### *Wildland Fuel Landscape file (LCP)*

Elevation  
Slope  
Aspect  
Surface Fuel Model  
Canopy Cover  
Canopy Height  
Crown Base Height  
Crown Bulk Density  
Fuel Loading Model  
Tree List

graphic from [www.firemodels.org](http://www.firemodels.org)

#### A.2.1.1 Current-condition LCP

In the spring of 2012, “out of the box” LANDFIRE Data<sup>1</sup> LCP was used for the preliminary testing of the concept of using FSim and WFAT (Wildland Fire Assessment Tool) to help determine wildfire hazard in the Mokelumne Analysis. At this time it was determined that FlamMap5 would be used instead of the WFAT (though this tool shows great promise in providing spatial fire effects outputs) because WFAT required the use of two raster themes that were experimental and/or cumbersome to deal with.

<sup>1</sup> [www.landfire.gov](http://www.landfire.gov) version 1.0.0

The results of our test runs were presented to the MACA Technical Committee and their feedback and a subsequent field trip to the project area helped identify the following calibration needs for the base LANDFIRE vegetation data:

1. Barren areas in the higher elevation were under represented.
2. Chaparral shrublands were also under represented in the area dominated by the LANDFIRE vegetation type of California Blue Oak-Foothill Pine (#2114).
3. Herbaceous - grassland were under represented in many areas below 4,000 feet elevation.
4. Agricultural areas below 4,000 feet elevation also seemed under represented.
5. LANDFIRE vegetation type Red Fir Forest and Woodland (#2032) seemed over represented in areas above 4,000 feet that appeared to be mountain shrublands.

An expert opinion crosswalk between CALVEG<sup>2</sup> and LANDFIRE Existing Vegetation Type (EVT) was developed by USFS Fuels Planner - Phil Bowden & USFS Fire Ecologist - Neil Sugihara to make the above listed adjustments to the LANDFIRE Vegetation data files. Using GIS, the initial CALVEG adjusted LANDFIRE vegetation Type (**EVT**), Cover (**EVC**), and Height (**EVH**) raster files were created by Phil Bowden. These raster files were then used in the 0.12 version of the LFTFC<sup>3</sup> (LANDFIRE Total Fuel Change) Tool for ArcGIS 10 to make the required calibrated LCP.

LFTFC uses rule sets for all EVT, EVH, EVC, and Fuels Disturbance Code (FDIST) combinations to determine Fuel Model assignment. Fuel canopy attributes are calculated by standard Forest Vegetation Simulator/ Fire Fuels Extension<sup>4</sup> (FVS/FFE) forest growth simulation model runs by FDIST, EVT, EVH, and EVC combinations. The LFTFC tool performs all calculations at the pixel level, not the stand level.

At a later date, GIS Specialist Allison Mead – National Forests in Florida – used the Model Builder in ArcMap to make the CALVEG adjusted LANDFIRE EVT, EVC, and EVH in a systematic way covering a slightly larger area than the initial raster files that Phil Bowden made. These final calibration raster files were completed for both LANDFIRE versions 1.1.0 & 1.0.5. Because version 1.1.0 has some imbedded vegetation changes (2001 -2008), the calibrated LANDFIRE version 1.0.5 (circa 2001) was used to bring both baseline and treatment scenario LCPs forward to the baseline year of 2008 using the LFTFC tool. This method avoided modeling a disturbance on vegetation data that already had been changed. The baseline scenario used the 2001- 2008 LANDFIRE Fuel Disturbance grid (FDIST) with the addition of a custom FDIST code applied only to Working Forest treatments.

The project-specific calibrated LANDFIRE version 1.1.0 (circa 2008) was used by other modeling specialists that needed 2008 baseline vegetation information as part of our project, but was not used for fire modeling.

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<sup>2</sup> CALVEG Info: <http://www.fs.fed.us/r5/rsl/projects/mapping/accuracy.shtml>

<sup>3</sup> LFTFC & WFAT Info: <http://www.frames.gov/partner-sites/nifft/tools/nifft-current-resources/>

<sup>4</sup> FVS/FFE Info: <http://www.fs.fed.us/fmfc/fvs/>

**Note:** The LFTFC can also help in reducing seam lines at LANDFIRE zone boundaries. This is done by making constant fuel model rule sets at the project level across LANDFIRE mapping zones. For the Mokelumne landscape there are two LANDFIRE zones involved.

#### A.2.1.2 Treated-condition LCP

The 0.12 version of the LFTFC tool was used again to create the necessary raster files to make the treatment scenario landscape files (LCP). The LFTFC tool uses a Fuels Disturbance (FDIST) raster file to simulate disturbance such as wildland fire and vegetation treatments. Also, LFTFC can change the four different fuel canopy attributes by a percentage. This level of detail for modeled vegetation treatments seems to be appropriate for this landscape scale analysis but would be of questionable value at the project scale.

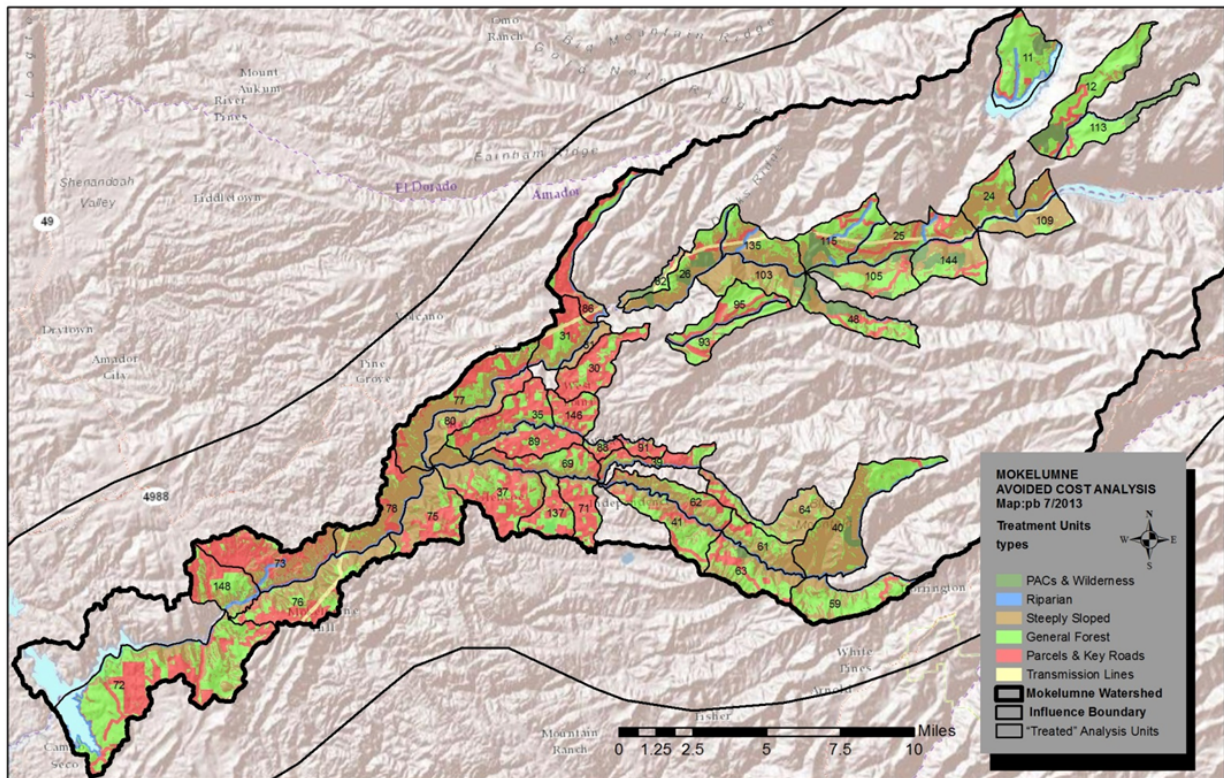
The matrix below (Table A.1) was used by the treatment team to apply FDIST codes and fuel canopy change factors to modeled treatment areas (Map A.1) selected by this same group (see chapter 2).

**Table A.1 LFTFC below denotes calculated by the LFTFC tool**

<i>Land Type</i>	<i>FDIST</i>	<i>Canopy Code</i>	<i>CC factor</i>	<i>CH factor</i>	<i>CBH factor</i>	<i>CBD factor</i>
<b>Wilderness-Roadless</b>	<b>112</b>	<b>1</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>
<b>CSOPACs</b>	<b>112</b>	<b>1</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>
<b>Riparian</b>	<b>312</b>	<b>1</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>
<b>Steeply Sloped</b>	<b>322</b>	<b>1</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>	<b>LFTFC</b>
<b>General Forest</b>	<b>322</b>	<b>2</b>	<b>0.8</b>	<b>1.2</b>	<b>LFTFC</b>	<b>LFTFC</b>
<b>Key Roads</b>	<b>322</b>	<b>3</b>	<b>0.7</b>	<b>1.4</b>	<b>LFTFC</b>	<b>LFTFC</b>
<b>Parcels with Structures</b>	<b>322</b>	<b>3</b>	<b>0.7</b>	<b>1.4</b>	<b>LFTFC</b>	<b>LFTFC</b>
<b>Transmission Lines</b>	<b>322</b>	<b>4</b>	<b>0.7</b>	<b>0.6</b>	<b>LFTFC</b>	<b>LFTFC</b>

The FDIST is the input layer that simulates recent disturbances and is required when using the LFTFC tool. The FDIST is available from the LANDFIRE Data Distribution Site for disturbances prior to 2009. Most of the model parameters for FSim and Flamamp5 were held constant from the baseline scenario to the treatment scenario; the only thing that changed was the LCP fuel and canopy characteristics shown in the matrix and map.

Map A.1



### A.2.2 Historical weather

All weather and related Fire Danger indexes data were obtained from the National Fire Danger Rating System (NFDRS) for the Mount Elizabeth (#43605) Remote Automated Weather Stations (RAWS) (<http://raws.fam.nwcg.gov/>). This RAWS is located in southern part of the Mokelumne landscape. Other RAWS were considered, including Beaver (#42601) and Mount Zion (#42701). The Mount Elizabeth has, in general, higher wind speeds during the fire season, wind direction for the 10:00 AM – 8:00 PM time period, and has a good mix for wind directions from the two other stations considered. The reliable weather history and the fact the FPA also uses Mount Elizabeth data were factors in station selection. Using the Mount Elizabeth data in the program FireFamilyPlus (<http://www.firemodels.org/index.php/national-systems/firefamilyplus>), the seasonal trend of ERC and the joint monthly distributions of wind speed and direction were determined. This information is used by FSim to produce artificial weather streams with the same statistical properties as the weather records inputted into FireFamilyPlus. These weather streams enable generation of the thousands of artificial ERC trends for the fire season in FSim. This RAWS is also used by FSim to randomly and independently draw a wind speed and direction for each day of a simulation.

### A.2.3 Historical fire occurrence

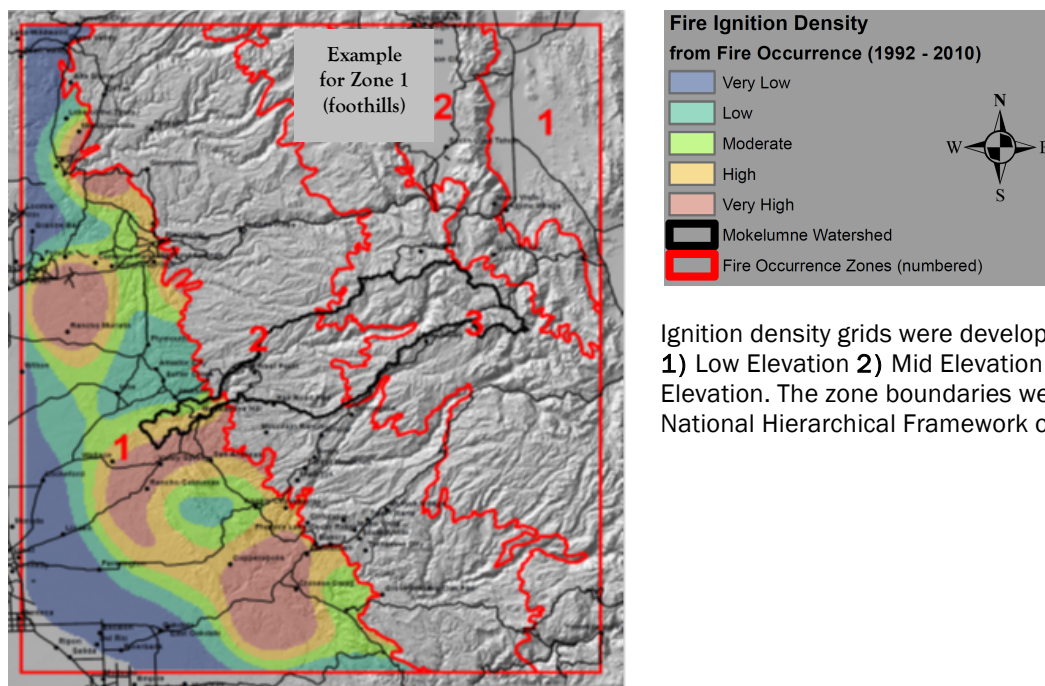
Historical wildfire occurrence data is needed to parameterize and calibrate FSim. The data used in this modeling was the spatial database of wildfires in the United States, 1992-2010 (Short 2013), developed for FPA. This dataset includes fire occurrence from all jurisdictions within the local

area. From this dataset, spatial and temporal analyses were conducted to generate inputs to FSim. The historical wildfire occurrence data was gathered from an area two-times the size of the zones modeled in FSim and that data was then proportioned to zone sizes. This was an effort to get a larger sample size of fire occurrence data.

### A.2.3.1 Spatial

Since fires do not start uniformly over a landscape, an ignition density grid (Map A.2) was developed to enable FSim to locate simulated fire ignition proportionally to where they happened in the past (1992-2010). FSim models the probability of large fires, so the purpose for using historic fire locations was because the fires that escape the initial fire suppression response are likely to become multiday events.

**Map A.2**

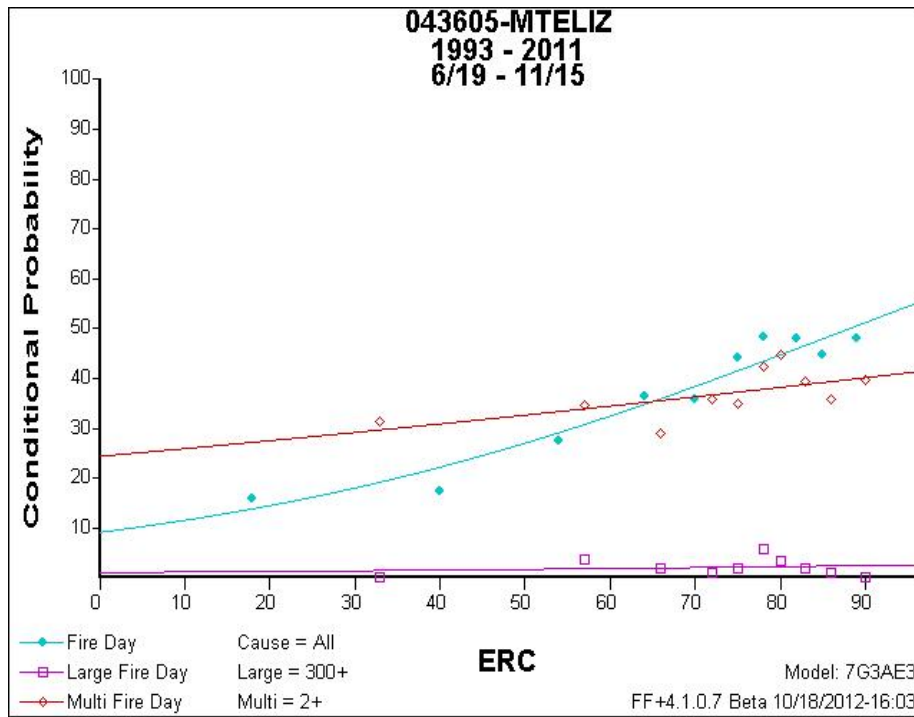


Ignition density grids were developed for three zones: **1)** Low Elevation **2)** Mid Elevation and **3)** High Elevation. The zone boundaries were based on the National Hierarchical Framework of Ecological Units.

### A.2.3.2 Temporal

An analysis of the probability of a large fire starting on a given day in a season was accomplished by using the program FireFamilyPlus, which associates the historic wildfire occurrence data with the weather and fuel moisture from the RAWS (Figure A.2). As discussed earlier, FSim is intended to simulate the large spreading fires and as such FSim constrains the growth of simulated fires to days when the ERC is  $\geq$  the 80th percentile recorded at the RAWS.

Figure A.2



Conditional large fire probabilities (as shown on the graph to the left) were developed for same three zones as listed on the previous page: 1) Low Elevation 2) Mid Elevation and 3) High Elevation.

### A.3 Fire modeling specifics

#### A.3.1 FlamMap5

Once the baseline fire modeling landscape (LCP) was completed, an initial FlamMap5 run was performed with the parameters listed in Table A.2. Early testing of sediment production modeling was done by using these initial flame length outputs in addition to the vegetation data to determine modeled soil burn severity. Subsequent concerns and discussions by MACA Technical Committee members about the high proportion of landscape being classified as high severity compared to recently burned areas in the Sierra Nevada led to multiple FlamMap5 simulations to try to calibrate closer to recent historic soil burn severity. The final calibration used the parameters listed in yellow below and had better proportions of low, moderate, and high severity as related to historic. Fuel Moisture used in the FlamMap 5 simulations are the average values that correlates to the 80<sup>th</sup> percentile ERC data from Mount Elizabeth RAWS (March 20 – November 1, 2002 – 2012). All simulated wind directions were uphill. Final Calibration wind speed is the 10 minute average at 20' under 80th percentile ERC.

Table A.2

FlamMap5 Run	20' Wind	Crown Fire Model	Fuel Moisture %					
			1hr	10hr	100hr	Herbaceous	Woody	Foliar
Initial	15 MPH	Scott	4	5	6	45	86	100
Final Calibration	12 MPH	Finney	4	5	6	45	86	100

### A.3.2 FSim

All FSim Simulations were done by zone (1 Low Elevation, 2 Mid Elevation, and 3 High Elevation). Each zone was modeled separately and had a unique set of historic wildfire occurrence data, along with an ignition density grid that allowed simulated fires to start only in one zone but were able to spread anywhere on the common LCP. This zone methodology helped to account for differences in the seasonality, frequency, and the suppression response of wildfire due to differences in elevation and vegetation type. A total of 33 calibration FSim simulations were completed for the MACA. Calibrations outputs for “large fires” (>300 acres) were compared to the historic wildfire occurrence data. Statistics compared were the mean annual number of fires, mean annual large fire area burned, and the mean large fire size. To speed up the calibration process, FSim calibrations were done using 270 meter resolution with 20,000 simulated seasons; these simulations took approximately 20 minutes per zone to run. Based on the calibration runs, adjustments were made in FSim to some parameters, such as the rate of fire spread to find a reasonable match to the historic large fire occurrence statistics. Once a reasonable match was found, a final FSim simulation was done for each zone using 90-meter resolution for 40,000 simulated seasons. Final simulations took approximately 6 hours per zone to run. The final 90-meter raster grid of Burn Probability (BP) results from each of the 3 zones added together in GIS to make one composite 90-meter BP raster grid. All other outputs produced by FSim, including the ESRI shapefiles containing the final perimeter of each simulated fire, were retained for possible analysis.

#### A.3.2.1 Statistical tests of final FSim outputs

We used the Statistical Analysis System (SAS) to statistically compare the distributions of fire size and seasonality of fires from the historic data (FPA) to the FSim output data by zone.

#### A.3.2.2 Fire Season distributions

There were not any statistical differences between mean Julian start dates for FPA vs. simulated fires in zones 2 and 3 (two sample t-test, P-values = 0.88 and 0.16 for zones 2 and 3 respectively, mean start dates 234 vs. 235 and 225 vs. 234 for FPA vs. simulated fires in zones 2 and 3, respectively). Start dates for FPA vs. simulated fires in zone 1 were statistically different (two sample t-test, P-value <0.001). However, the differences in mean start dates for zone 1 may have been an artifact of the data and may not be of practical significance when considering the distribution of start dates as a whole. The difference in mean start dates (212 vs. 230, FPA and simulated fires, respectively) is reflected by additional simulated fires in the latter half of the season as evidenced by a difference in the mode of the distributions of only two days (224 vs. 222, FPA and simulated fires, respectively). In addition, the latest zone 1 FPA fire start date was five weeks earlier than FPA fires in either zone 2 or 3 (294 for zone 1 vs. 329 for zones 2 and 3). In reality, there is not any practical reason that the fire season in zone 1 would end five weeks earlier than in either zone 2 or 3.

#### A.3.2.3 Fire Size

The distributions of fire sizes were similar for FPA and simulated fires across all zones, with the number of fires being inversely proportional to fire size (i.e. the largest number of fires fell in the smallest size class and number of fires decreased as fire size increased). However, the larger fire

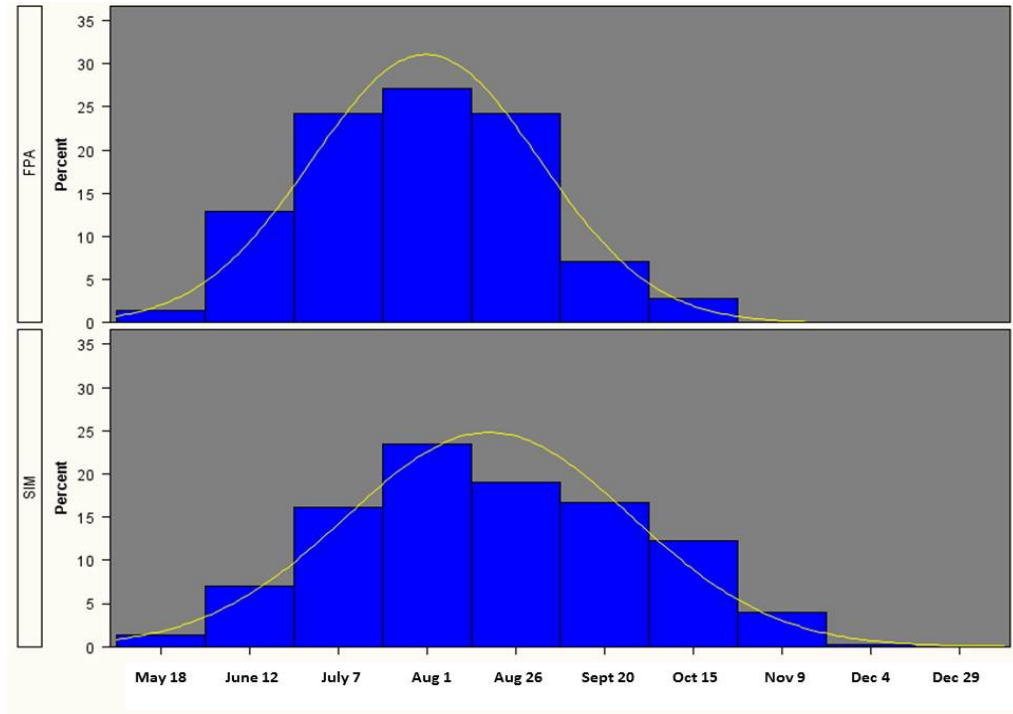
classes were fully populated for simulated fires but not for FPA fires, primarily due to the much larger number of simulated fires (70 vs. 24167, 39 vs. 28975, and 31 vs. 24453 for FPA vs. simulated fires in zones 1, 2, and 3, respectively). Graphical comparisons of these distributions are on the following three pages (Figure A.3).

**Figure A.3**

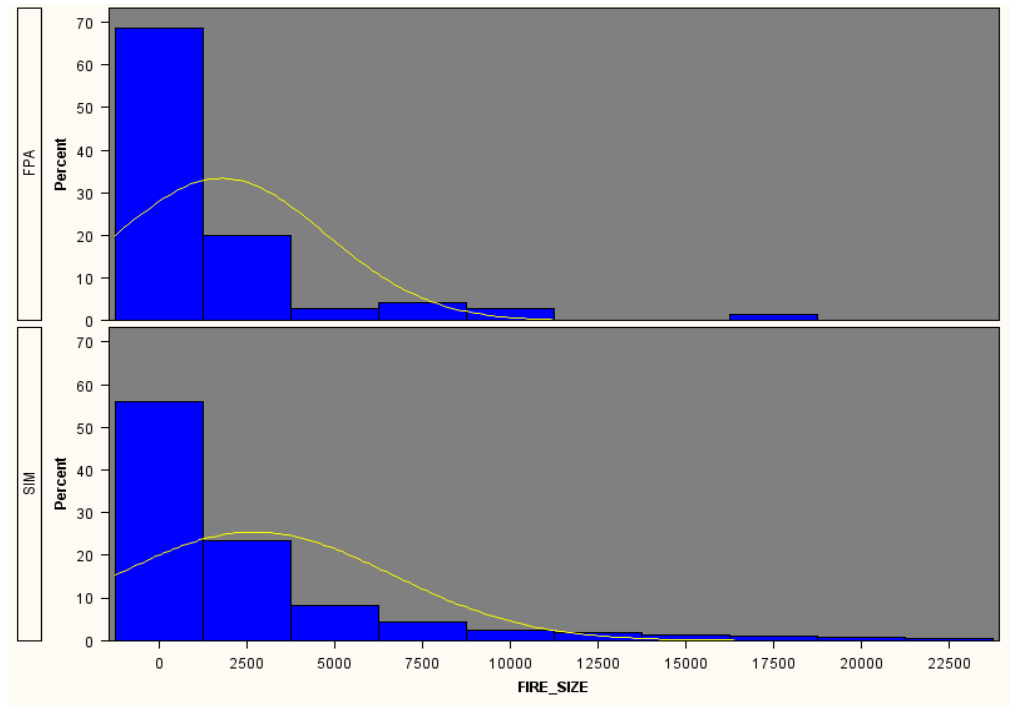
Zone 1

(Low Elevation)

Percent of fires  
by date



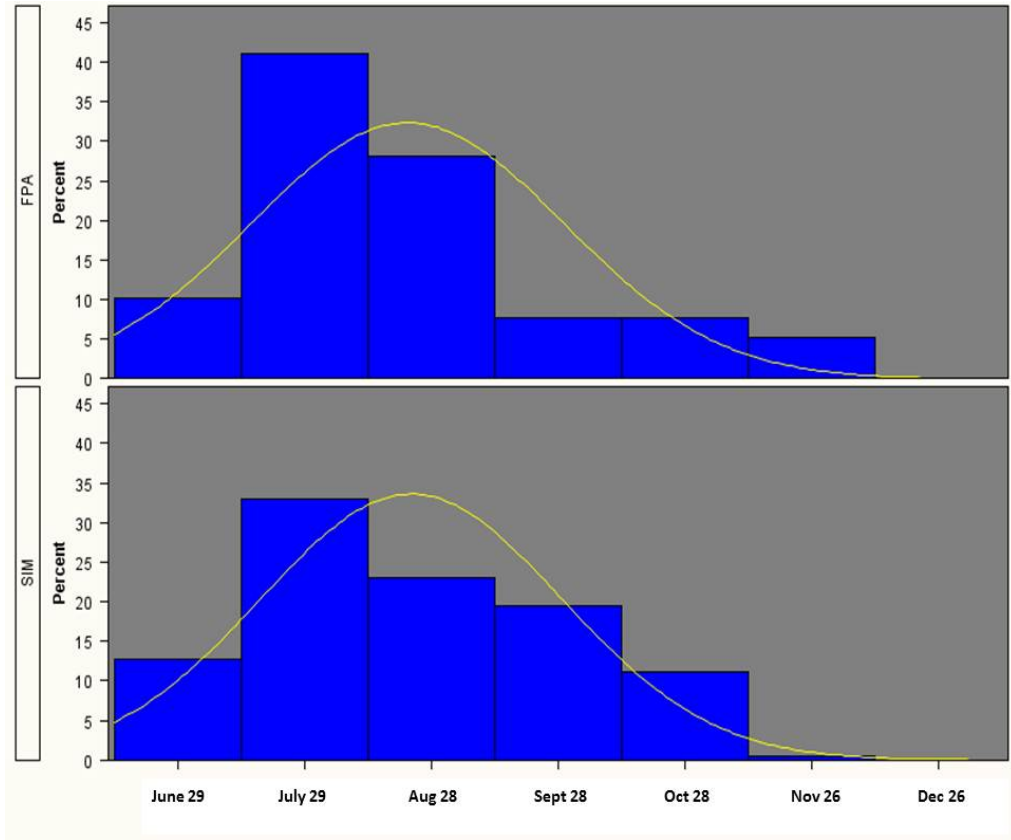
Percent of fires  
by acres



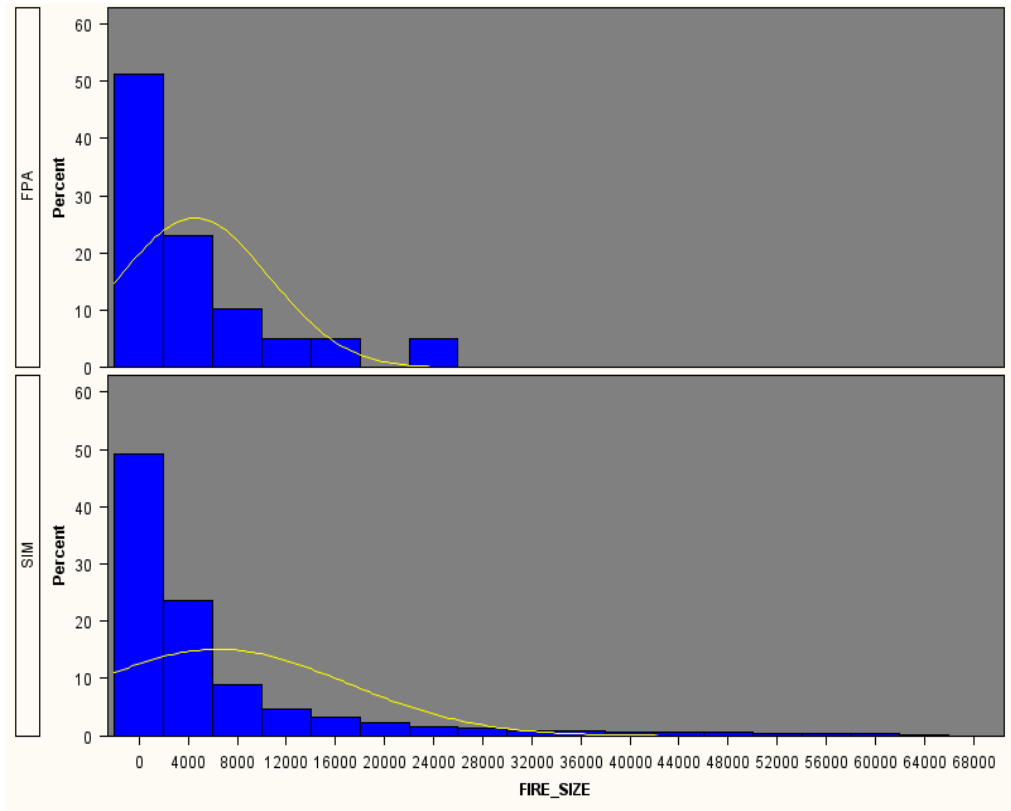
Zone 2

(Mid Elevation)

Percent of fires  
by date



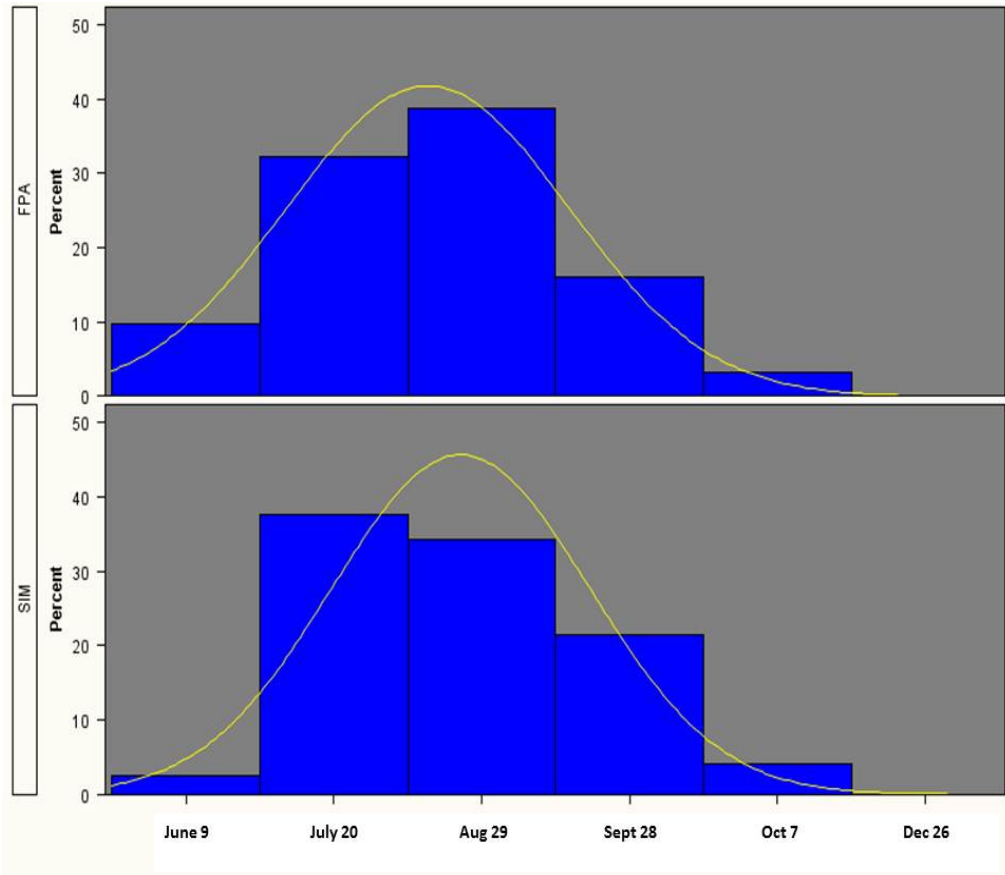
Percent of fires  
by acres



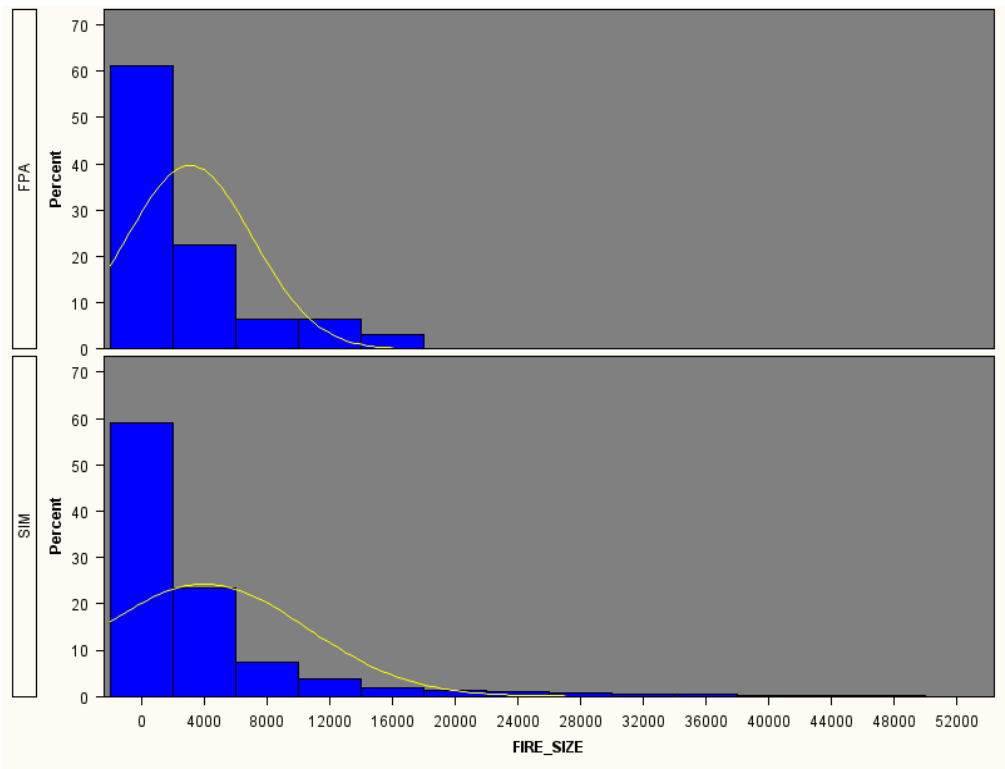
Zone 3

(High  
Elevation)

Percent of fires  
by date

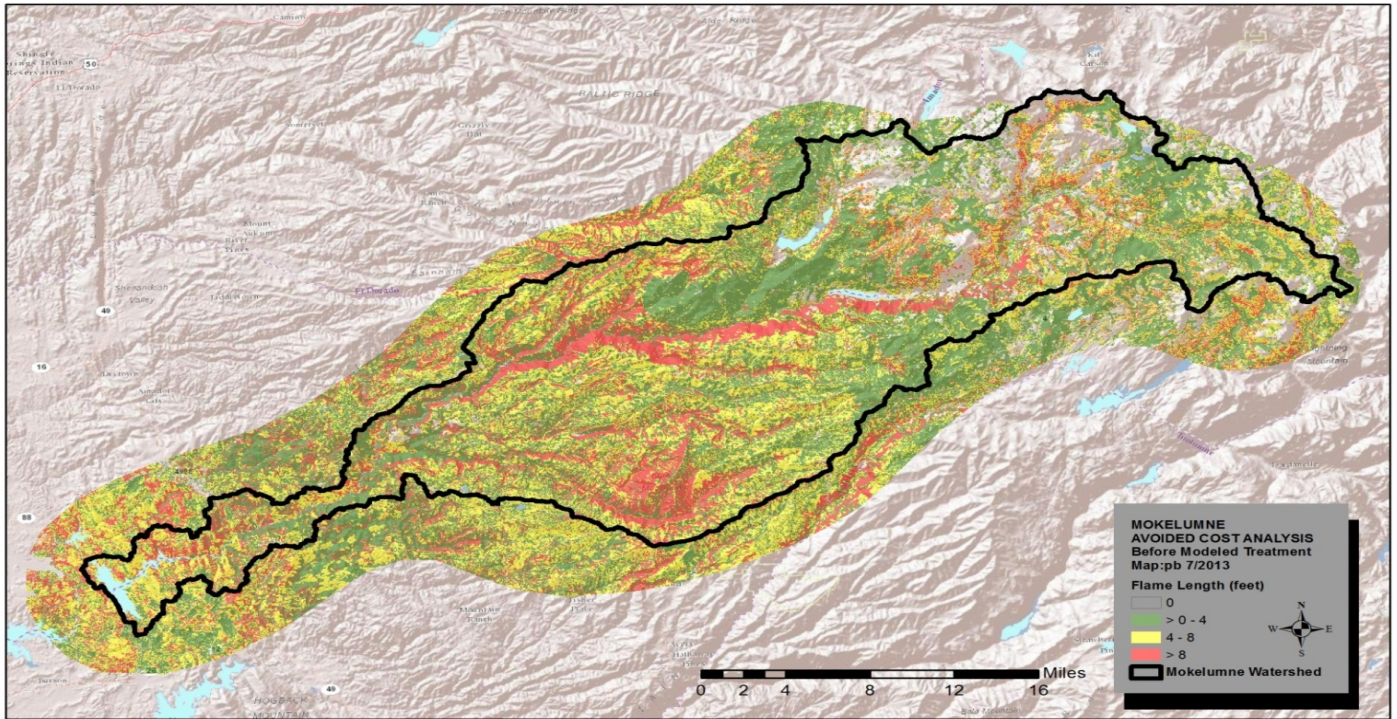


Percent of fires  
by acres

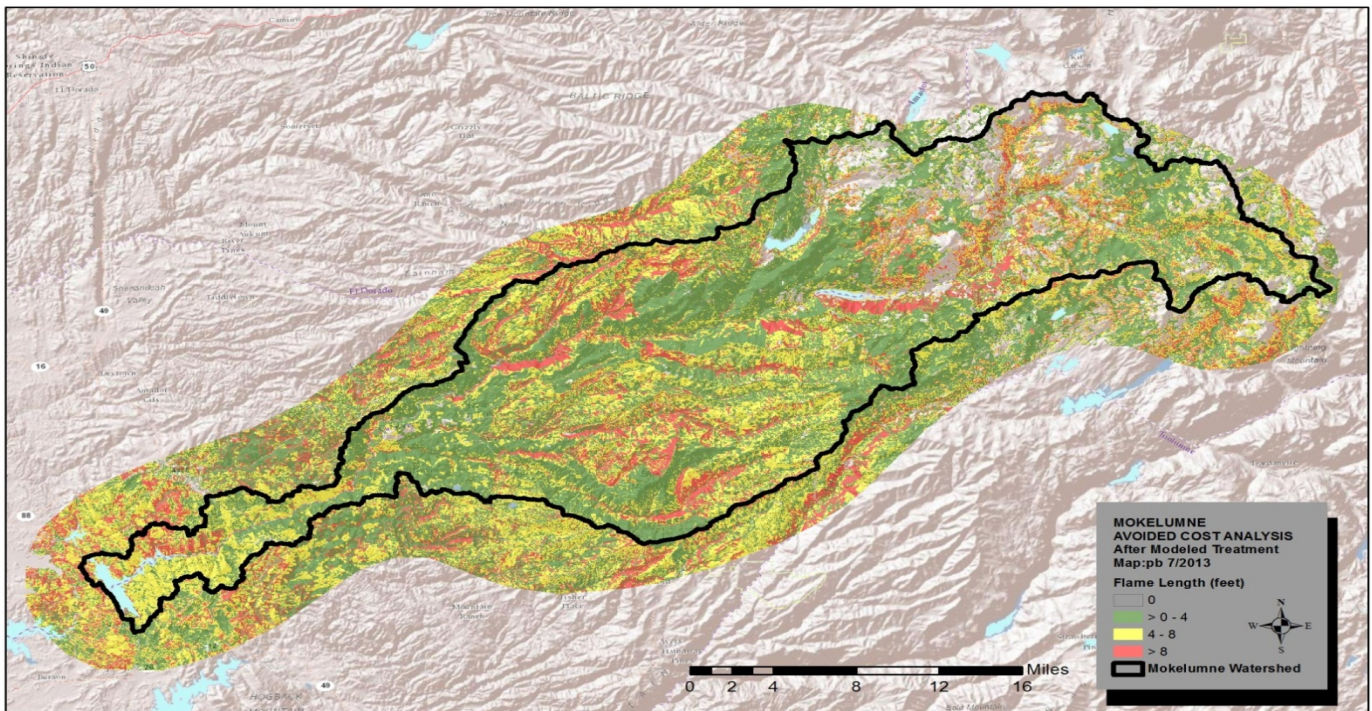


## A.4 Results

Map A.3 Final FlamMap5 results – flame lengths: pretreatment



Map A.4 Final FlamMap5 results – flame lengths: posttreatment



Since wildfire hazard can be quantified as the likelihood of experiencing a wildfire and the intensity, or severity, of a wildfire if one occurs, map outputs are:

- *Intensity* - FlamMap5 Flame Length
- *Likelihood* - FSim Burn Probability for both the before & after treatment scenarios.

Table A.3 is one way to think about rating hazard in a relative way; this could be a possible way of prioritizing areas of concern if the consequences to values are equal.

**Table A.3**

Intensity	Likelihood		
	Low Probability	Moderate Probability	High Probability
Low Flame Length	Low, Low	low, Moderate	Low, High
Moderate Flame Length	Moderate, Low	Moderate, Low	Moderate, High
High Flame Length	High, Low	High, Moderate	High, High

Many interim maps that spatially combined burn probability and flame length were developed in order to map the relative wildfire hazard to help inform the selection of the hypothetical treatment locations. This fire modeling did not link this hazard to consequences in monetary values in the Mokelumne watershed; this modeling was done to provide fire hazard metrics only.

The outputs of annualized large fire acres can be calculated via multiplying the total of the burn probability for all the grid cells by the area of each cell in acres, located in table A.4. This table summarizes the annualized large fire acres for the before & after treatment scenarios within the Mokelumne watershed and also displays the possible associated fire suppression costs by fire size classes. To develop the annualized figures, the total burn area for all 40,000 fire seasons were added together and then divided by 40,000 to get totals per year across the full 40,000 season timeline.

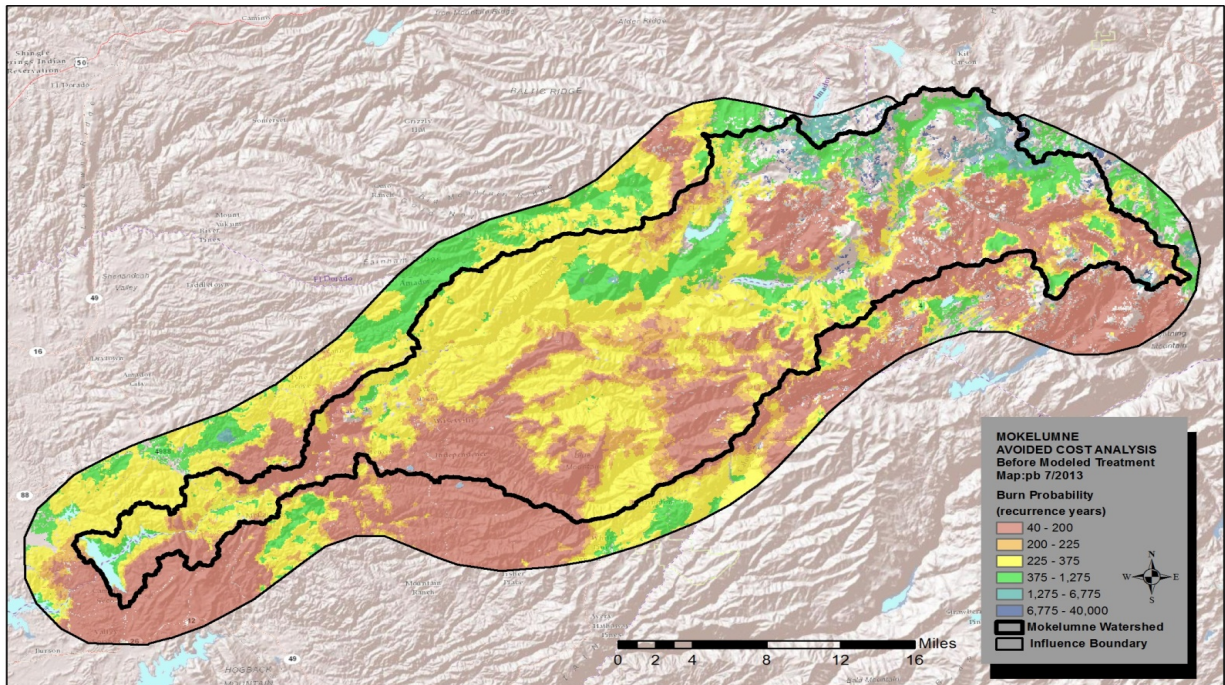
**Table A.4**

	Annualized Acres	Class E size	Class F size	Class G size
Cost per Acre		\$1,616.00	\$690.00	\$1,358.00
After Treatment	1213	\$1,960,208.00	\$836,970.00	\$1,647,254.00
Before Treatment	1480	\$2,391,680.00	\$1,021,200.00	\$2,009,840.00
Change	-267	-\$431,472.00	-\$184,230.00	-\$362,586.00

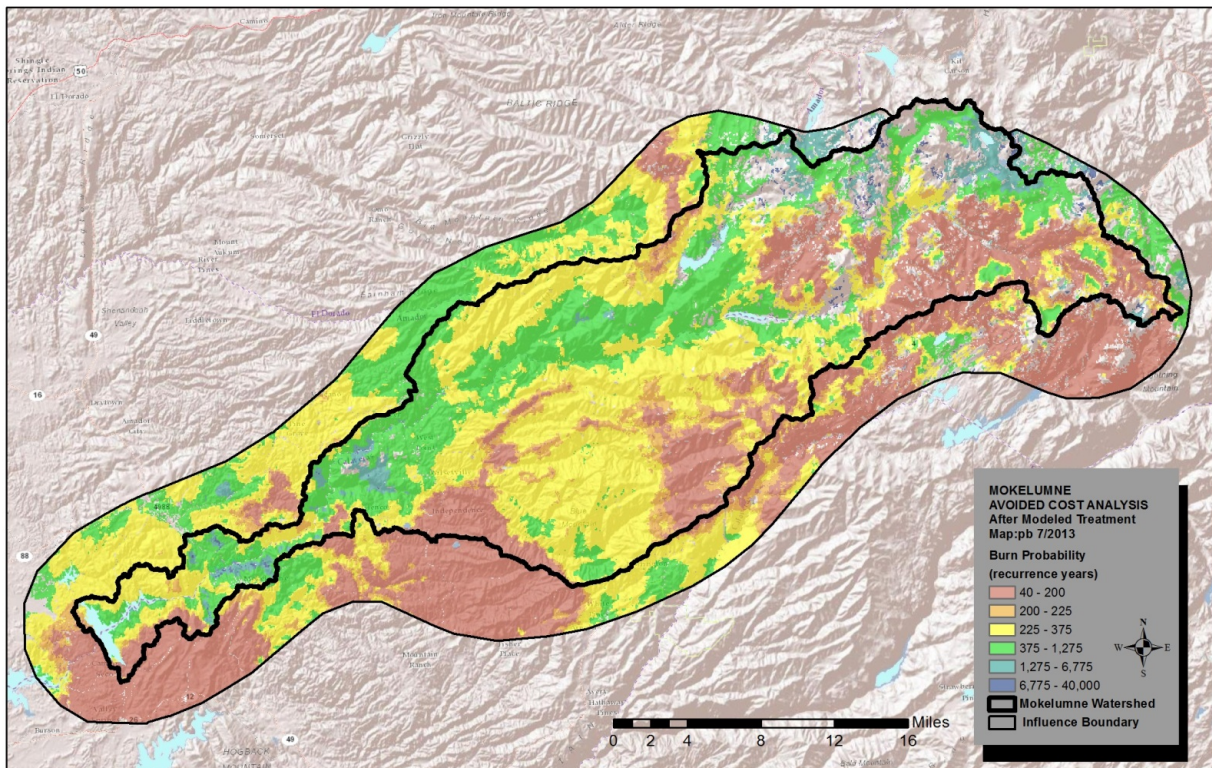
Fire Costs are actual fire costs for the Eldorado National Forest (2001 -2010) adjusted for inflation.

**Size of wildfire:** Class E - 300 acres or more, but less than 1,000 acres; Class F - 1,000 acres or more, but less than 5,000 acres; Class G - 5,000 acres or more.

Map A.5 Final FSim results – burn probability (in recurrent years): pretreatment



Map A.6 Final FSim results – burn probability (in recurrent years): posttreatment



## References

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# Mokelumne Watershed Avoided Cost Analysis: Why Sierra Fuel Treatments Make Economic Sense

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## Disclaimer

This report is rich in data and analyses and may help support planning processes in the watershed. The data and analyses were primarily funded with public resources and are therefore available for others to use with appropriate referencing of the sources. This analysis is not intended to be a planning document.

The report includes a section on cultural heritage to acknowledge the inherent value of these resources, while also recognizing the difficulty of placing a monetary value on them. This work honors the value of Native American cultural or sacred sites, or disassociated collected or archived artifacts. This work does not intend to cause direct or indirect disturbance to any cultural resources.

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## Contact Information

### For More Information:



**David Edelson**  
dedelson@tnc.org  
**Kristen Podolak**  
kpodolak@tnc.org



**Kim Carr**  
kim.carr@sierranevada.ca.gov  
**Nic Enstice**  
nic.enstice@sierranevada.ca.gov



**Sherry Hazelhurst**  
shazelhurst@fs.fed.us